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EFFECTS OF MOISTURE CONTENT ON RESILIENT PROPERTIES OF RECYCLED CONCRETE AGGREGATES (RCAs)

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ABSTRACT

In pavement design, resilient modulus of a pavement material is one of the key design parameters. Resilient modulus of a granular pavement material can be measured using repeated load Triaxial (RLT) test or estimated using empirical models. For conventional granular pavement materials, a significant amount of resilient modulus data and empirical models to estimate this key design parameter are available. However, RCA is a relatively new granular pavement material and therefore no such data or empirical models are available. In this study, a number of RLT tests were conducted on RCA sample to investigate the effects of moisture content on its resilient modulus (M_r). It was observed that the resilient modulus of RCA increased with a number of loading cycles but decreased as the moisture content was increased. Further, using RLT test results, empirical models to estimate the resilient modulus of RCA were enhanced and validated.

Keywords: Repeater Load Triaxial, Recycled Concrete Aggregates, Resilient Modulus, Water Content

INTRODUCTION

Population growth and development /redevelopment activities in the globe have led to rapid increase in construction and demolition waste (C&D waste). Recycling of C&D waste has been identified as one of the best ways to manage C&D waste due to its environmental, social, and economic benefits. In 2008- 2009, Australia produced a total of 19 million tons of C&D waste [1] of which 55% was recycled. The C&D waste recycling sector in Queensland, Australia is reasonably well established and therefore Queensland government has targeted to increase the recycling of C&D by 50%, 60% and 75% successively in years 2014, 2017 and 2020 [1]. Therefore, it is needed to explore the applications of these recycled materials. About 40 % of C&D waste is demolished concrete and recycling concrete can generate aggregates called “Recycled Concrete Aggregates (RCA).

Roads are one of the biggest infrastructures in any country. In road construction, a large volume of aggregates is used as granular layers, stabilised granular layers, and aggregates for asphalt production. At present, crushed rocks are the preferred granular material used in road construction. Use of RCA as granular pavement material reduces the disposal of C&D waste to landfills and the depletion of natural resources (rocks).

Lack of data on properties and performances of RCA as a pavement granular material has limited its use in pavement structures. Further, the properties and performances of RCA can be inconsistence due to the presence of impurities such as asphalt, brick, and glass in RCA. In addition, water content in RCA could have significant effect on the properties and performances of RCA as a granular pavement material.

Jr et al., [2] and Bennert et al.,[3] studied the performance of RCA and reclaimed asphalt pavement (RAP) using RLTs and concluded that RCA performed better than the RAP materials when considering the development of the permanent strain. Nataatmadja and Tan [4] reported that well-graded RCA produces a higher resilient modulus under low deviator stress and it may be caused by the un-hydrated cement within the RCA. Even though, some more studies on the performance characteristics of RCA are reported [5, 6], further studies are needed to investigate the effects of water content in RCA on its resilient modulus. Resilient modulus is one of key material elastic properties required in pavement design.

This paper presents the results of a series of RLT tests conducted on RCA samples with different moisture content. The results of the test series are then used to enhance the constitutive models, which are used to estimate the resilient modulus of granular materials, by taking the water content of RCA into account. Further, the applicability of the enhanced models to estimate the resilient modulus of the RCA is validated using additional RLT test data.

TESTING MATERIAL

A commercially available RCA product termed as RM001 was employed in this experimental program. The material was obtained from a concrete recycling company in Queensland and it was sourced from clean concrete and can be considered free from other impurities such as glass, bricks, wood, soil, and asphalt. Figure 1 shows the texture of RM001.

Fig. 1 The appearance of RM001

Particle size distribution (PSD) of RM001 was obtained by performing sieve analysis in accordance with Australian standards, AS1289.3.6.1-2009 [7]. As shown in Fig. 2, the PSD of RM001 was plotted with upper and lower boundaries of PSDs of base layer granular materials specified by Queensland Department of Main Roads [8]. The RM001 has maximum and minimum particle size 25.4 mm and 0.18 mm respectively. It can be seen that the particles larger than 20 mm shifted the upper limit of specification and the particles smaller than 0.6 mm propped below the lower limit of the specification.

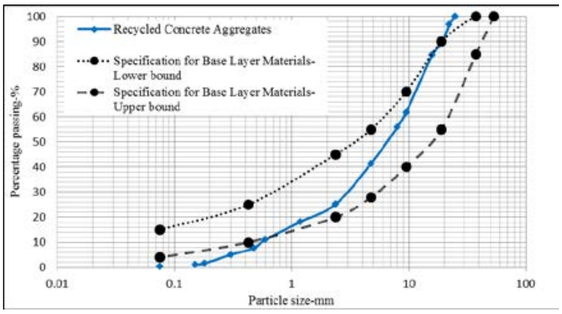

Fig. 2 PSD of test material (RM001)

RM001 was tested for atterberg limits in accordance with Australian and Queensland Department of Transport and Main Roads Queensland (QDTMR) standards [9-11], water absorption following the test method specified QDTMR [12, 13], and standard proctor compaction test in accordance with Australian Standards [14] and the results are shown in Table 1.

Atterberg limits of RM001 are within the range specified by QDTMR for standard granular pavement material. However, the water absorption capacity of RM001 is much higher than that of standard pavement granular material. This could be caused by residual cement and cement mortar paste around the aggregates in RCA. When compaction properties of test material are compared with those of standard pavement granular material, RCA has smaller maximum dry density (MDD) and greater optimum moisture content (OMC) than that of standard granular pavement material. This could be due to lesser fines content and higher absorption capacity of RCA compared to standard granular pavement material.

Table 1. Physical properties of RCA

Property	Values	
	RCA (RM001)	Standard granular pavement material
Liquid Limit (PL) [%]	21.00	*Max: 25 [8]
Plasticity Index (PI)	5.40	*Max: 6 [8]
Linear Shrinkage (LS) [%]	1.00	*Max: 3.5 [8]
Water absorption (particles smaller than 4.25 mm) [%]	5.35	<10 [15]
Water absorption (particles greater than 4.25 mm) [%]	6.50	<10 [15]
Specific gravity (Gs)	2.64	2.85 [16]
Maximum dry density (MDD) [g/cm^3]	1.75	>1.79 [15]
Optimum moisture content (OMC) [%]	13.20	8-15 [15]

*Max=Maximum

TESTING APPARATUS

To obtain the resilient modulus of RCA samples, the Repeated Load Triaxial (RLT) apparatus of which the schematic diagram is shown in Fig. 3 was employed in this study. The apparatus can accommodate a cylindrical specimen with 100 mm diameter and 200 mm height. The confining pressure up to 1000 kPa is applied by pressurizing air in the cell and the applied confining pressure is continuously monitored by transducer connected to the cell. The pneumatic actuator connected to the vertical shaft can apply repeated load/stress with different waveforms on the sample under stress or strain controlled conditions. The actuator has the capacity to apply the maximum load of 12kN and has the maximum stroke of 30 mm. The vertical deformation of the specimen is calculated by averaging the vertical deformation measured by two

LVDTs attached to the vertical shaft as shown in Fig. 3. RLT test is commonly conducted under undrained condition and therefore no volume change unit is available. Saturated and unsaturated specimen can be tested in the apparatus with continuous monitoring of pore-water pressure by the transducer connect to the bottom of the specimen. LVDTs, Pore-pressure and cell pressure transducers, and load cell are connected to logging system to collect the responses of these transducers at specified time interval.

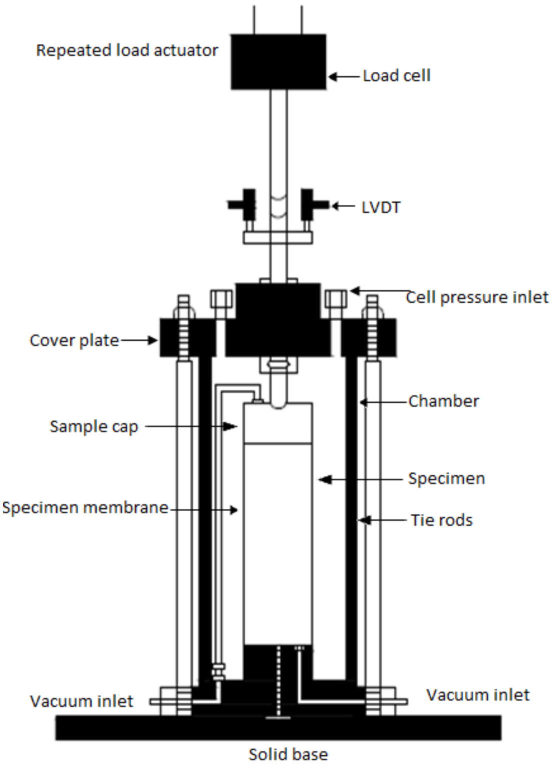

Fig. 3 The schematic diagram of RLT apparatus used

METHODOLOGY

Table 2. Summary of test conditions

Moisture content (%)	Dry density (g/cm^3)	Confining pressure (kPa)	Degree of saturation (%)	Dynamic deviator stress (kPa)
11.6	1.75	125	60	175, 325, 475, 625
13.2	1.75	125	68	175, 325, 475, 625
14.5	1.75	125	75	175, 325, 475, 625
15.5	1.75	125	80	175, 325, 475, 625

Note: At each stress stage, 10,000 load repetitions were applied.

The resilient modulus (M_r) of RCA and the effects of moisture content on M_r were investigated by performing a series of RLT tests on RCA specimens. As shown in Table 2, tests were performed using three dynamic deviator stresses (σ_d) of 175, 325, 475, and 625 kPa, with confining pressure (σ_3) of 125 kPa. Tests were conducted at four different water content values and the dry density equal to MDD was maintained for all tests.

Specimen Preparation

Oven dried material was mixed with pre-determined water content (e.g: 11.6, 13.2, 14.5, 15.5 %) and left overnight in sealed containers for moisture homogenization. Then the material was compacted in to a split mould of 100 mm diameter and 200 mm height to achieve the pre-determined dry density of 1.75 g/cm^3. The compaction of the specimen was done in three layers. The bulk mass required to achieve the dry density of 1.75 g/cm^3 in the mould was calculated and one-third of that mass was used for each layer and numbers of standard compaction blows were applied to reach one-third of the mould height. This method was repeated to other two layers to get a specimen prepared for a RLT test.

The compacted specimen was then enclosed in 0.8 mm thick rubber membrane and set in the RLT apparatus. The specimen was sealed at the top and the bottom of the specimen and 125 kPa confining pressure was applied and allowed to consolidate for about 2 hours.

Loading and data interpretation

Once the sample was consolidated under 125 kPa confining pressure, the wave form shown in Fig. 4 was repeatedly applied under undrained conditions. For each sample, the wave form was repeated 10,000 times for each dynamic deviator stress (σ_d) stage (e.g: 175, 325, 475, and 625 kPa).

Figure 5 shows a typical stress vs strain response for a RLT test and how to obtain resilient modulus (M_r) and permanent/plastic strain (deformation) corresponding to a given loading cycle.

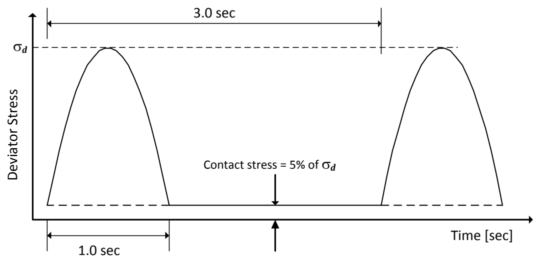

Fig. 4 Illustration of the vertical (deviator) stress waveform applied

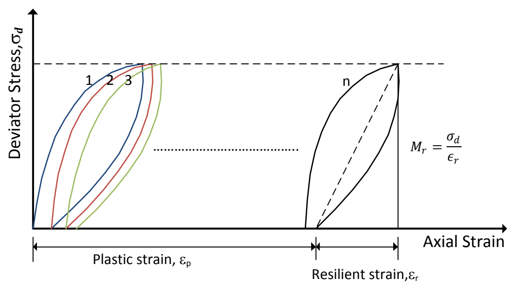

Fig. 5 Typical stress vs strain response in RLT test

RESULTS AND DISCUSSIONS

A series of RLT tests were conducted under the conditions given in Table 2 to investigate the effects of water content on resilient properties (permanent deformation/strain and resilient modulus (M_r)) of RCA. Further, using the resilient modulus data obtained from the tests, a constitutive model was enhanced to predict/estimate the resilient modulus of RCA and its applicability was validated using additional test data.

Accumulation of permanent (plastic) strain in RCA

Figure 6 depicts the accumulation of vertical plastic strain with numbers of loading cycles and how it is affected by the sample moisture content and dynamic deviator stress (σ_d).

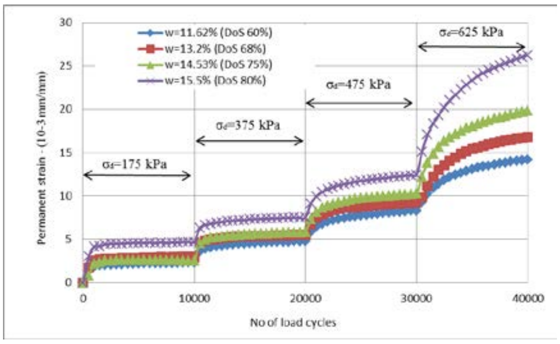

Fig. 6 Accumulation of vertical plastic strain with numbers of loading cycles

As shown in Fig. 6, for a given confining pressure and a dynamic deviator stress, the plastic strain increases with numbers of loading cycles. However, the rate of increase in plastic strain (plastic strain per loading cycle) decreases with numbers of loading cycles tending to achieve a long-term, steady-state response (no accumulation of plastic strain and each response is hysteretic). This implies that a finite amount of energy is absorbed by the material on each stress-strain excursion. Once a purely resilient response has been obtained, the material is said to have "shake down" and the maximum stress level that this condition is achieved is termed the "plastic shakedown limit". Numbers of researchers [17, 18] observed the shake down state and the plastic shakedown limit for pavement granular materials such as crushed rocks. It can be seen that RCA tends to behave like natural granular material under repeated load and the applied stress conditions in this experimental program seem to be less than the plastic shakedown limit of RCA except σ_d.

The vertical plastic strain increases with increase in sample moisture content and the principal stress ratio (σ_d/σ_3). As the moisture content is increased, the particles are more lubricated to facilitate their movement into air-voids. This may increase the accumulation of plastic strain. As the stress ratio is increased, the lateral confinement becomes smaller compared to the dynamic deviator stress. This may allow greater lateral displacement in the sample that cause to increase the plastic vertical deformation.

Resilient modulus of RCA

Figure 7 shows how resilient modulus (M_r) of RCA varies with numbers of loading cycles. It can be seen that, for a given stress condition which is smaller than the plastic shake down limit of RCA, M_r increases significantly with the first few numbers of loading cycles and then it increases with decreasing rate tending to approach the steady-state condition (zero increase in Mr with loading cycles) which can be termed as shake down response. Densification of the sample with the first numbers of loading cycles could cause the increase in resilient modulus. Once a steady-state response is achieved, neither plastic strain nor the densification is accumulated or occurred and therefore, no increase in M_r with numbers of loading cycles can be observed once the steady-state response is achieved. A numbers of researchers [19, 20] observed this phenomenon for natural crushed rocks and it can be seen that RCA behave like natural crushed rocks under repeated loads though its M_r is much less than that of high standard granular pavement materials (Mr=300-700MPa) specified by Austroads Ltd, Australia [21].

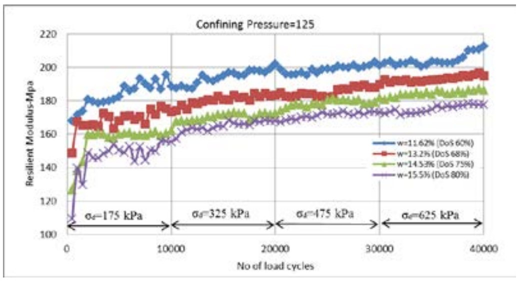

Fig. 7 The variation of resilient modulus (Mr) of RCA with number of loading cycles

For each test with different water content, M_r

was calculated at 10,000th loading cycle of each stress stage and the results are shown in Fig.8. It can be seen that M_r decreases with increase in material's moisture content and increases slightly with increase in stress ratio (σ_d/σ_3) or bulk stress θ ($\sigma_1+\sigma_2+\sigma_3$).

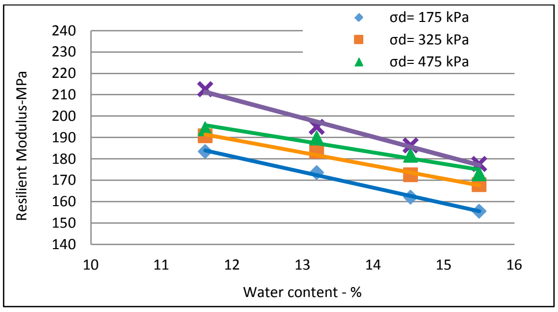

Fig. 8 The variation of resilient modulus of RCA with moisture content and stress level

More water in the sample lubricates the particles to reduce the frictional resistance between RCA particles and that eventually leads to reduce the stiffness (M_r) of the sample.

Constitute model to estimate M_r of RCA taking water content into account

It is not practicable to perform RLT tests to obtained M_r of pavement granular materials. Therefore, numbers of constitute models have been developed by researchers [22, 23] to estimate the M_r for granular road materials. There is no such model for RCA to predict/estimate its Mr, the following, more simple, constitute model is attempted to predict the M_r of RCA [22]:

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \tag{1}$$

Where,
M_r = Resilient Modulus
$\boldsymbol{p_a}$ = Atmospheric pressure (103.4 kPa)
$\boldsymbol{\theta}$ = Bulk stress $(\boldsymbol{\sigma_1+\sigma_2+\sigma_3})$
$\boldsymbol{\sigma_1}$ =Principal vertical stresses
$\boldsymbol{\sigma_3} = \boldsymbol{\sigma_2}$ =Principal radial stresses (confining pressure)
k_1 and k_2 are model parameters

Non-linear regression analysis was used to fit the measured M_r in Fig. 8 to Eq. (1) and to obtain the model parameters k_1 and k_2 as a function of initial moisture content of RCA sample as shown below:

$$k_1 = -0.0435\ w + 1.3397 \tag{2}$$
$$k_2 = 0.0088\ w + 0.3009 \tag{3}$$

where, w = moisture content in percentage (%)

To validate the applicability of enhanced model to predict the M_r of RCA with different moisture content, a RLT test on RCA with 66 stress conditions was conducted according to the standard method of Austroad APRG 00/33-2000 [24]. The sample's initial moisture content was maintained at 13.8 %. Then, for all these 66 stress conditions, M_r was calculated and also predicted using Eq. (1), (2) and (3). Fig. 9 depicts the measured and predicted M_r values and they are well agreed. With further validation using the results of tests conducted at different moisture contents and stress conditions, it would be able to suggest the enhanced constitutive model to be used to predict/estimate the M_r of RCA.

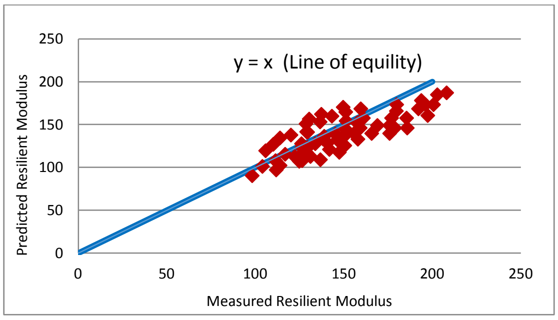

Fig. 9 Measured and predicted M_r for RCA sample with moisture content of 13.8%

CONCLUSION

In this study, the resilient properties of RCA and the effects of moisture content on these properties were investigated by a series of performing Repeated Load Triaxial tests. The following conclusions are drawn from this study:

- In terms of classification properties, RM001 (RCA) is comparable with standard granular pavement material specified by QDTMR.
- For a given stress condition, the resilient modulus of RCA decreases and the plastic strain of RCA increases with increase in moisture content.
- RCA tends to exhibit "shake down" response and "plastic shake down limit" that are observed in natural granular materials such as crushed rocks.
- The enhanced constitutive model will be able to use to predict the resilient modulus of RCA by taking moisture content and stress level of the material into account.

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